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High Explosive Testing of a Corrugated Metal Blast Shelter with Membrane Blast Doors

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HIGH EXPLOSIVE TESTING OF A CORRUGATED METAL BLAST SHELTER WITH MEMBRANE BLAST DOORS

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EXECUTIVE SUMMARY

In October 1983 the Defense Nuclear Agency (DNA) sponsored a high-explosive blast test, nicknamed DIRECT COURSE. This event simulated the blast effects from a one-kiloton nuclear detonation and provided an environment for the testing of selected shelters and components for their structural integrity and resistance to blast.

Under work for the Federal Emergency Management Agency (FEMA), the Oak Ridge National Laboratory (ORNL) fielded a set of experiments at the DIRECT COURSE event which were directed toward testing methods of reducing the cost of blast shelter for small groups of people, such as critical workers. Six items were tested: three 1/4-scale models of a corrugated metal blast shelter and three full-size blast door closures for such a shelter.

The ORNL blast shelter, a low-cost prototype, was fabricated from the type of corrugated metal culvert which can be found in drainage and highway construction use. The design tested at DIRECT COURSE was a modification of a shelter designed by Donn Metal Products (Donn, Inc., Westlake, Ohio). The ORNL modifications were intended to improve the ease of entry, the protection against initial nuclear radiation, and the hardness of the entryway while keeping the construction costs low.

Each of the three shelters tested at DIRECT COURSE was 180 cm (6 ft.) long by 60 cm (2 ft.) in diameter, was buried about 60 cm (2 ft.) below ground level, and represented a 1/4-scale reduction of a full-size shelter capable of supporting 12 to 18 occupants. The entryway to the shelter was a vertical length of metal culvert clamped to a TEE-section at one side of the shelter body. One end of the shelter body was fabricated as a frustum of a cone; while, the other was a low-cost closure fabricated from a flat, circular piece of sheet metal welded to an angle iron hoop.

Three identical scale model shelters were buried at field locations with expected overpressures of 0.35, 0.7, and 1.4 MPa (50, 100, and 200 psi). All three shelters survived the blast, even though the actual overpressures were 10 to 20% higher than were expected. The shelter at the expected 1.4 MPa (200 psi) location was actually subjected to an overpressure of 1.55 MPa (225 psi) and suffered a non-catastrophic buckling of the low-cost shelter body end closure. A slight, concave deformation of this shelter body at the entryway TEE-section was the only other sign of damage for any of the shelters tested. The clamped joints in the shelter entryway showed no distortion or deformation in any of the three test items.

The ORNL yielding membrane blast door is a novel concept based upon the elastic behavior of thin metal membranes. An original theory for this behavior was used successfully at ORNL in the early 1970's in the design of foil blast gauges. The metal membrane deforms predictably, much like a soap bubble, under shock loading. This design has the potential to save both weight and cost over that of conventional blast doors.

Each of the three blast doors tested at DIRECT COURSE was about 90 cm (35 in.) in diameter and consisted of a flat, circular piece of thin sheet metal attached at its circumference to an edge beam or support hoop. Each door rested upon a frame or "support collar" fabricated from rolled angle iron hoops. The angle iron geometry provided the appropriate sills, rain lips, windscreens, and soil support footing. The door/frame assembly rested atop a 60 cm (2 ft.) length of 76 cm (30 in.) ID corrugated metal culvert, which simulated the entryway to an actual shelter.

Three yielding membrane blast doors were positioned at field locations with expected overpressures of 0.35, 0.7, and 1.4 MPa (50, 100, and 200 psi). The three test items employed two different designs. For the 0.35 and 0.7 MPa (50 and 100 psi) doors, the stainless steel membrane was 1.3 mm (0.050 in.) thick, and the edge beam was a hoop rolled

from 2.5 by 6.4 cm (1 by 2.5 in.) carbon steel bar stock. For the 1.4 MPa (200 psi) door, the membrane was 2.0 mm (0.080 in.) thick, and the edge beam was rolled from 5 cm (2 in.) diameter steel pipe, which was subsequently filled with concrete for strength. It was hoped that these variations in design and overpressure would bracket the range over which failure might occur.

All three doors survived the blast. The actual overpressures measured during the blast are described above in the discussion of the shelter test results. The measured permanent deflection of each membrane door was about half of what had been expected from the previous theory on foil blast gauges; however, a computer simulation of the membrane's theoretical dynamics showed that this peculiar behavior can be explained by the very short duration (approximately 100 ms) of the positive phase for this blast. Although there was no other distortion or deformation in the doors or in the supporting frame, the support collars were pushed about 10 cm (4 in.) into the ground at each location.

A summary of results and the conclusions from this set of experiments follows:

- The corrugated metal shelter design proved to be successful and showed promise for reducing the cost and improving the hardness of such shelters.
- Survival of the clamped entryway joints may indicate that expensive field welding is unnecessary.
- The low-cost end closure for the shelter body needs more development, since this item partially failed at the highest overpressure.
- The full-scale yielding membrane blast door concept was successfully demonstrated.
- Since none of the doors failed, there is ample room in the design for even further reduction in weight and cost.
- More refinement in the design of the support collar (door frame) is needed, since it was slightly pushed into the ground.

It is recommended that the next step in the design and testing of this blast shelter concept should accurately reflect a working model. Either megaton-range blast loading with a long positive phase duration or appropriately scaled model testing will be required. Both clamped and welded joints should be tested. Design modifications to the yielding membrane blast door and to its support collar (door frame) should include the necessary thermal protection, hinges, latches, and other operating features as required in actual service in an occupied blast shelter. A full-size shelter should be built and tested for habitability.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the courtesy and cooperation of Earl May of Knoxville Metal Culvert Company, who assisted with the design specifications and fabrication of our 1/4-scale corrugated metal shelters. We would also like to acknowledge the efforts of Chuck Wilton of Scientific Service, Inc., in assisting us with the installation and the post-test inspection and recovery of our experiments from the White Sands, New Mexico, test bed. Without Chuck's assistance, it is highly unlikely that this work could have proceeded on schedule and within budget.

Reviews of this report and numerous constructive comments were provided by Capt. Ed Raska, Jr. of DNA and by Ralph Swisher and Don Bettge of FEMA.

Jeni Riordan and Judy Coleman of ORNL also deserve special recognition for their part in editing and word processing, respectively, and for their much-needed assistance in assembling this document.

CONVERSION FACTORS FOR SI UNITS

English units have been retained in the body of this report. The report is directed toward the construction of blast shelters and their components, and it refers to commercially available materials and sizes commonly expressed in English units. The report makes reference to earlier work and to construction drawings which are expressed entirely in English units. The conversion factors for SI units are given below:

To Convert From:	To:	Multiply By:
Foot (ft.)	Meter (m)	0.3048
Inch (in.)	Meter (m)	0.0254
Pound-mass (lb)	Kilogram (kg)	0.4536
Pound-force/in^2 (psi)	Pascal (Pa)	6894.8

HIGH EXPLOSIVE TESTING OF A CORRUGATED METAL BLAST SHELTER WITH MEMBRANE BLAST DOORS

Abstract

In October 1983 the Defense Nuclear Agency (DNA) sponsored a high-explosive blast test, nicknamed DIRECT COURSE. This event simulated the blast effects from a one-kiloton nuclear detonation and provided an environment for the testing of selected blast and fallout shelters for their structural integrity.

Under work for the Federal Emergency Management Agency (FEMA), the Oak Ridge National Laboratory (ORNL) fielded a set of experiments at the DIRECT COURSE event which were directed toward reducing the cost of blast shelter for small groups of people, such as workers in critical industries (keyworkers). Six items were tested: three scale models of a corrugated metal blast shelter and three full-size blast door closures for such a shelter.

The three shelters survived blast overpressures up to 2.55 MPa (225 psi), a level which is equivalent to being approximately 800 m (0.5 mile) from a 1 megaton nuclear detonation. Each shelter model was 180 cm (6 ft.) long by 60 cm (2 ft.) in diameter, was buried about 60 cm (2 ft.) below ground level, and represented a 1/4-scale version of a full-size blast shelter which would be capable of supporting 12 to 18 occupants.

The three full-size, 90 cm (35 in.) diameter, blast doors for such a shelter also successfully resisted the same range of blast overpressure. Each door weighed less than 45 kg (100 lb) and incorporated a novel, yielding-membrane design. These sheet metal membranes were between 1.3 and 2.0 mm (0.050 and 0.080 in.) thick and were supported by an edge beam (hoop).

It is anticipated that such structures, both shelters and blast doors, can be incorporated into a blast shelter concept which can be constructed for less than $500 per shelter occupant.

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1. INTRODUCTION

1.1 BACKGROUND

The objective of part of the work being done for the Federal Emergency Management Agency (FEMA) by the Oak Ridge National Laboratory (ORNL) is to find ways to reduce the cost of blast shelter for small groups of people, such as critical workers. Toward this end, ORNL has been developing a design concept based on corrugated metal culvert which is a modification of a Donn Metal Products shelter[7]. This modified design is intended to improve the protection against initial nuclear radiation, ease of access, and hardness of the entryway while keeping the construction costs down.

The concept developed at ORNL was described by C. V. Chester and D. W. Holladay in Reference 2. In that report, the authors advocated certain structural components which, if tested and proven, could be incorporated into a blast shelter design with an installed cost of less than $500 per shelter occupant. The inclusion of these selected test items in the DIRECT COURSE event was, in part, intended as a "proof test."

DIRECT COURSE was the nickname given to a high-explosive blast test which exposed selected structures, shelters, military systems and equipment to blast and thermal phenomena simulating the detonation of a nuclear weapon. The DIRECT COURSE event was one of a series (the MISTY CASTLE series) of such large scale, high-explosive tests conducted by the Defense Nuclear Agency (DNA). Other recent DNA tests include DICE THROW in 1976, MISERS BLUFF in 1978, and MILL RACE in 1981.

The DIRECT COURSE event was climaxed on October 26, 1983 by the chemical explosion of 552,000 kg (609 tons) of ammonium nitrate fuel oil (ANFO) contained in a 10.5-meter (35-ft.) diameter fiberglass sphere centered at a height of approximately 50 meters (165 ft.) above the

ground. Both the testbed and the elevated ANFO charge can be seen in Fig. 1. The event took place at the White Sands Missile Range in New Mexico. The blast effects were roughly equivalent to those from a one-kiloton nuclear detonation.

1.2 PURPOSE OF THE EXPERIMENT

The ORNL blast shelter concept uses a vertical entry to one side of the shelter and a lightweight blast door consisting of a yielding membrane supported by an edge beam. A conceptual drawing of the shelter appears in Fig. 2. The blast doors are described more fully in Section 2.2 but are basically circular sheet metal membranes with diameters of about 80 cm (32 in.) welded to a support hoop.

Three 1/4-scale shelters and three full-size blast doors were each tested at field locations with expected blast over-pressures of 0.35, 0.7, and 1.4 MPa (50, 100, and 200 psi). The three shelters were identical; the three blast doors were similar but had slight structural variations as described in Section 2.2. The parametric variation in overpressure was selected so as to bracket the range over which failure was expected to occur.

Each of these six items was tested for its ability to withstand the specified blast loading. The shelter model was intended to expose any problems caused by the unusual entryway geometry. It was particularly important to see if differential earth movement would cause failure of the joints between the entryway and the body of the shelter. In addition, a low-cost prototype of the shelter body end closure was tested. The end closure for one end of the shelter was a truncated cone, while the low-cost closure consisted of a circular sheet of mild steel welded at its rim to an angle iron which had been rolled in a hoop.

The major point of interest in the testing of the blast doors was the integrity of the membrane and of its support hoop. While not a primary study objective, the behavior of the support collar on which the blast door rested was also important.

ORNL—PHOTO 3135—84

Fig. 1 DIRECT COURSE Testbed at White Sands Missile Range

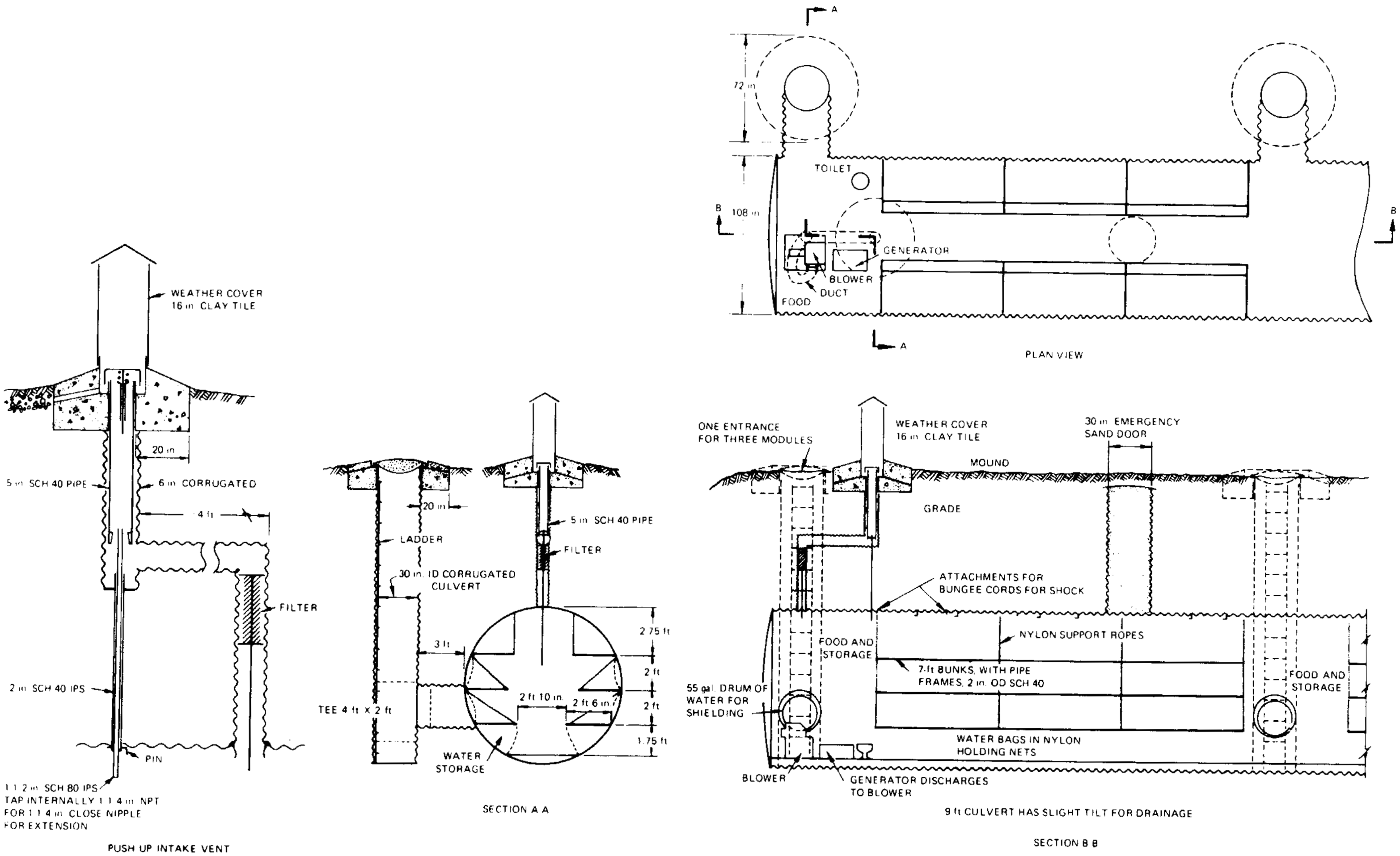

Fig. 2   ORNL Corrugated Metal Blast Shelter Conceptual Drawing

1.3 SCOPE OF THE EXPERIMENTS

There were no active data requirements or measurements for these experiments. Dimensional data on any post-test deformation or failure was expected to provide sufficient information on the behavior of these test articles. This information will be used to make modifications to the tested designs so as to further reduce the cost for such shelters.

2. DESIGN OF THE EXPERIMENTS

2.1 SCALE MODEL BLAST SHELTERS

The design for the scale model blast shelters appears in Fig. 3, and the parts list is given in Table 1. Each corrugated metal item was chosen from a standard set of "off-the-shelf," available metal culvert as used in drainage and highway construction.[1] The full-scale design[2] calls for a 9-foot diameter shelter body with 12 gauge (0.109 in.) wall thickness; however, Item Number 1 in Table 1 was the most dimensionally-compatible culvert available for 1/4-scale testing. The same is true for Items Number 2 and 3 which attempted to model the full-size, 30 in. i.d. entrance in 1/4-scale.

The conical end, Item Number 5 in Table 1, was fabricated from sheet metal that was thicker than required. The original design by Donn Metal Products[7] used a 12 gauge (0.109 in.) conical end of bolted corrugated metal for the 6 1/2 ft. diameter shelter end closure. A suitably scaled sheet metal thickness was not available to meet the required fabrication schedule for the 1/4-scale shelters for the DIRECT COURSE event.

The flat end, Item Number 6 in Table 1, was designed as a yielding membrane (see the discussion of the blast door design below) to take advantage of the soil arching behavior around the shelter. It was anticipated that, if this design were successfully tested, this end closure could be fabricated at a lower cost than other closures requiring elaborate cutting or forming operations.

All of the items in Table 1 were welded together with the exception of (a) the vertical entryway, which was clamped to the TEE section and (b) the flat end for the shelter, which was attached with sheet metal screws for ease of post-test inspection of the shelter interior.

Figures 4 and 5 show the shelter models being installed at the DIRECT COURSE test site. The shelters were buried about 2-ft. below ground level. There was no particular backfill requirement, but Fig. 5

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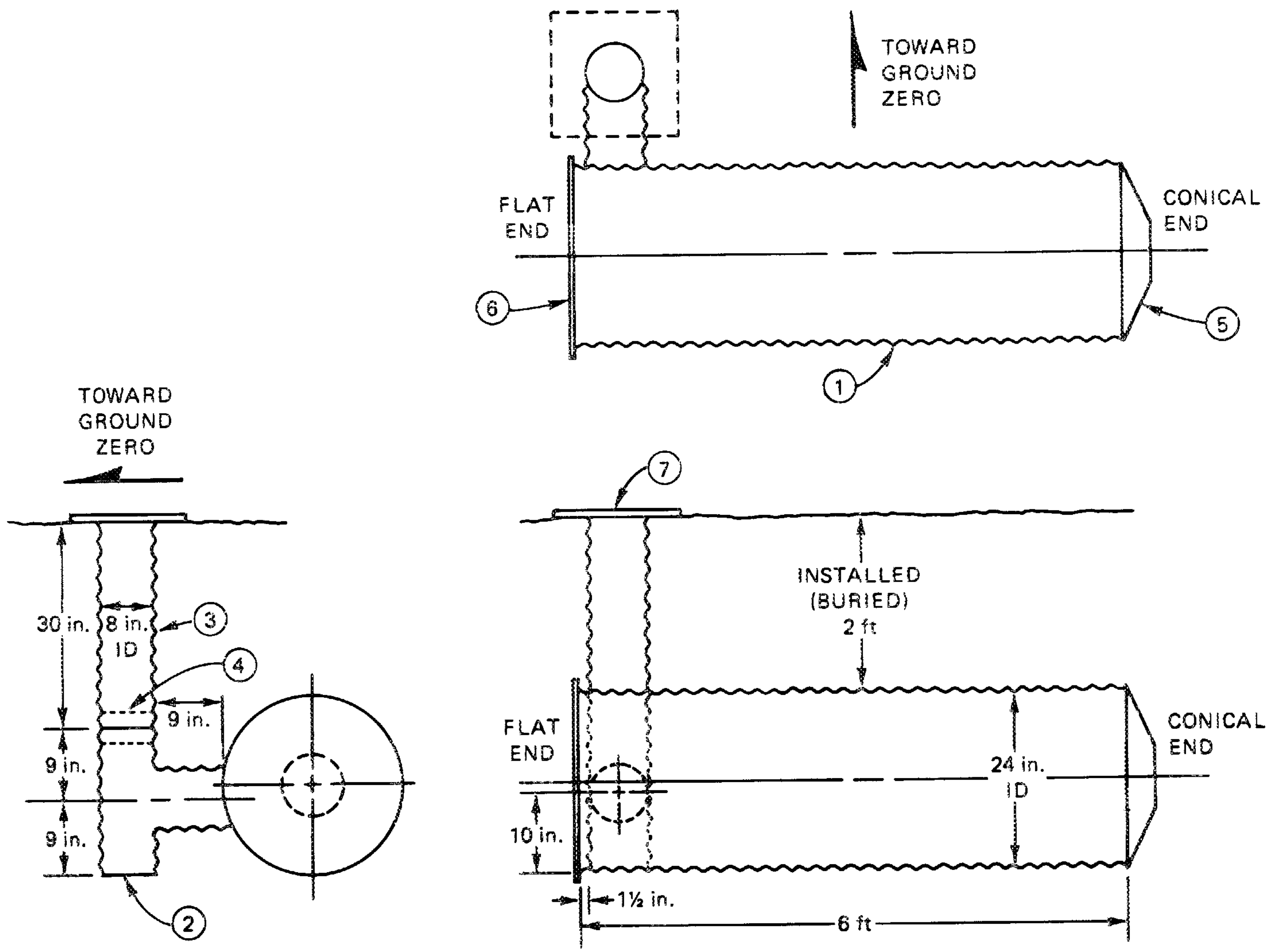

Fig. 3 1/4-Scale Blast Shelters for Testing at DIRECT COURSE

TABLE 1

Parts List for 1/4-Scale Corrugated Metal Blast Shelter

Item No.	Description
1	Shelter body: corrugated steel pipe, 24 inch i.d. X 6 ft. length, 16 gauge (0.064 in.) wall thickness with 2-2/3 X 1/2 in. helical corrugations
2	TEE section: corrugated steel pipe, 8-in. i.d., 18 in. run by 9 in. branch, 18 gauge (0.052 in.) wall thickness with 1-1/2 X 1/4 in. helical corrugations.
3	Vertical entryway: corrugated steel pipe, 8-in. i.d. X 30 in. length, 18 gauge (0.052 in.) wall thickness with 1-1/2 X 1/4 in. helical corrugations.
4	Two-piece band clamp with gasket: for 8-in. corrugated pipe.
5	Conical end: fabricated from 12 gauge (0.109 in.) sheet metal, 30° interior cone angle, 25 in. diameter base by 8 in. diameter end, closed with same gauge 8 in. diameter sheet metal.
6	Flat end: fabricated from 22 gauge (0.030 in.) sheet metal cut to 25-in. diameter, weld to 23 1/2 in. I.D. hoop of 1 X 1 X 1/8 in. steel angle iron (rolled flange-out).
7	Hatch cover: fabricated from 1/8 in. sheet metal cut to 15 in. square.

ORNL—PHOTO 0451—84

Fig. 4 Installation of the 1/4-Scale Shelter at the 100 psi Field Location

ORNL—PHOTO 0445–84

Fig. 5 Installation of the 1/4-Scale Shelter at the 50 psi Field Location

illustrates the lack of adequate backfill around the ends of the shelter to provide any appreciable amount of soil arching during the blast loading. However, the backfill around the vertical entryway and the TEE section did appear sufficient to provide some soil arching in this critical structural region.

Again, there was no active instrumentation in this set of experiments. The post-test condition, deformations, and/or failure modes were the primary study objectives.

2.2 YIELDING MEMBRANE BLAST DOORS

The ORNL concept for a lightweight blast door stems from a need to provide resistance to blast loading without the material cost or the bulk associated with a standard, massive blast door. "Why not," it seemed, "design a blast door which will give with the shock wave like a willow and not like an oak tree?" It appeared to be feasible to base such a design on the behavior of rupture disks or foil blast gauges, both of which have unique performance characteristics at specified pressures. In fact, the design of these novel, yielding membrane blast doors follows from earlier work done at ORNL on foil blast gauges.[3,4,6]

The ORNL yielding membrane blast door consists of a flat, circular piece of thin sheet metal, which serves as the membrane, attached at its circumference to an edge beam or support hoop. Two edge beam designs were tested. Figure 6 shows the blast door design which was tested at the 200 psi field location, while Fig. 7 illustrates the design for both the 50 and 100 psi tests.

The permanent plastic deformation of thin membranes subjected to blast overpressure was calculated by Dresner.[3,4] Dresner computed the deflections of a circular foil membrane from

$$H = 0.138 \left(\frac{D^2 P}{sT} \right) \qquad \text{(Eqn.1)}$$

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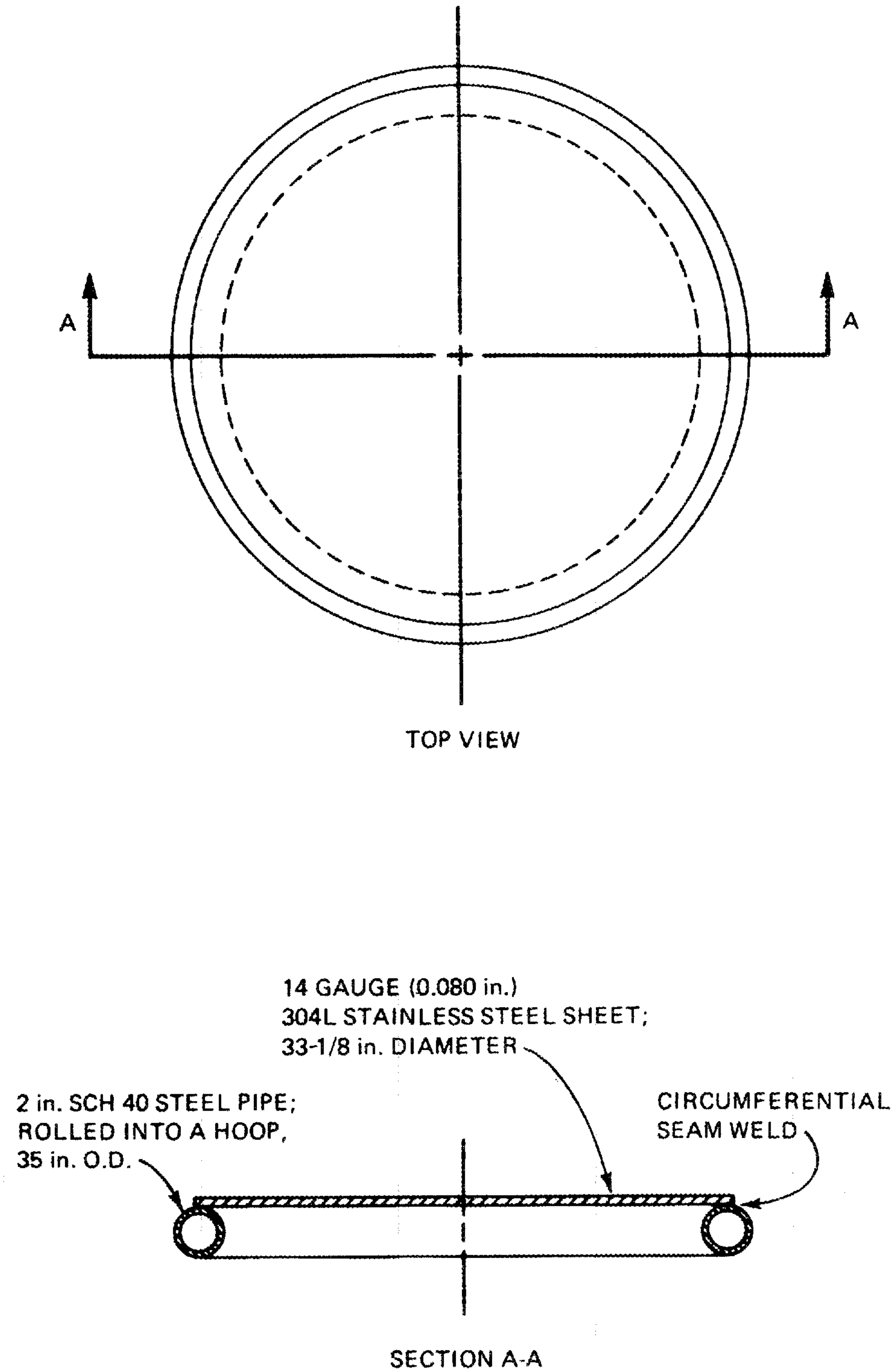

Fig. 6 Yielding Membrane Blast Door Design for Testing at 200 psi

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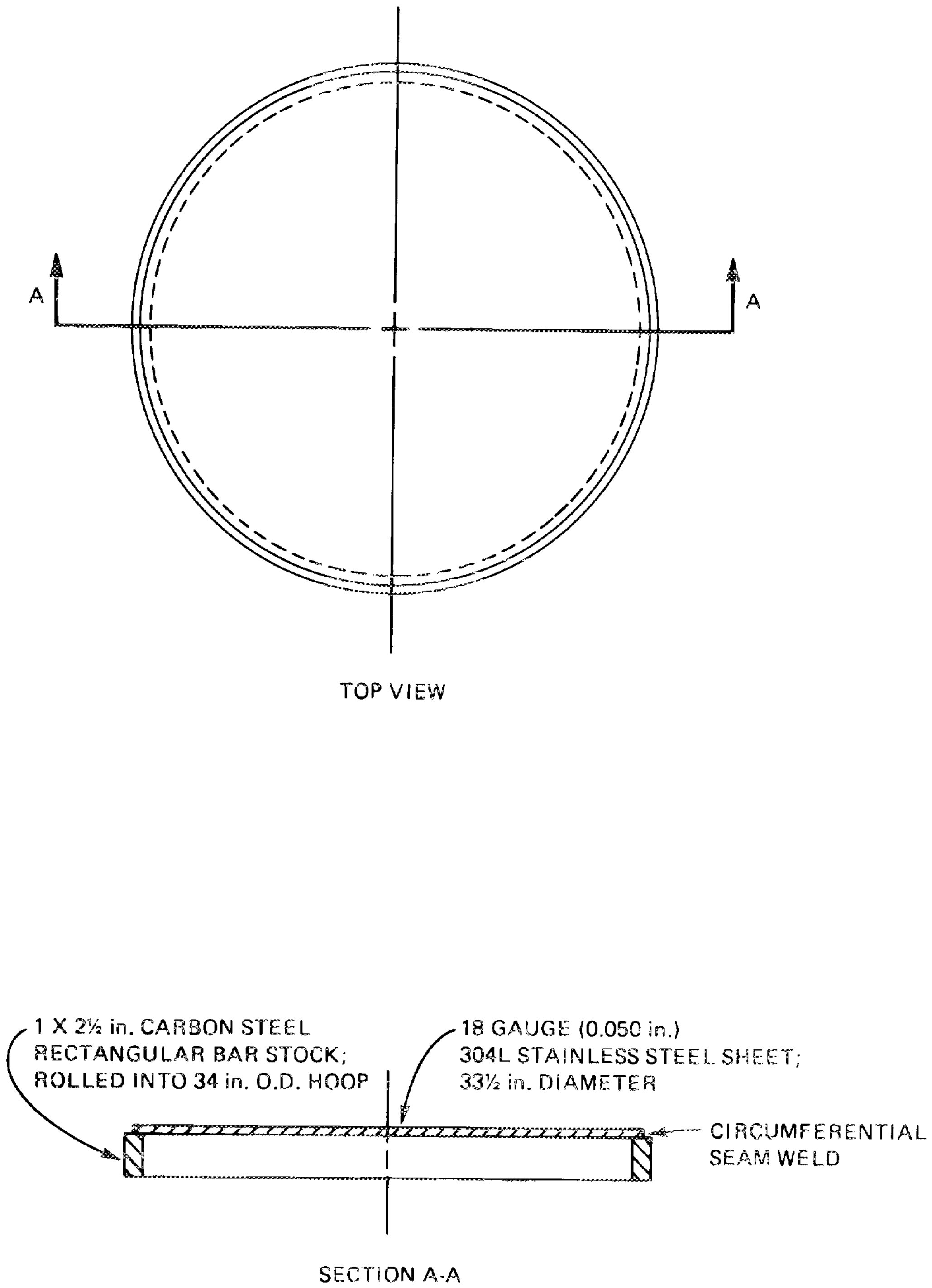

Fig. 7 Yielding Membrane Blast Door Design for Testing at 50 and 100 psi

where

H is the maximum permanent deflection of the membrane in inches,

D is the diameter of the membrane in inches,

P is the incident, normal shock pressure in psi,

T is the membrane's thickness in inches,

and

s is the stress developed in the membrane in psi.

Furthermore, Dresner calculated the average linear strain (e) in the membrane to be

$$e = 1.8 \left(\frac{H}{D}\right)^2. \qquad \text{(Eqn. 2)}$$

If one uses the two equations above and the physical dimensions of a given membrane, it becomes possible to predict a membrane's deflection at a specified overpressure via an iterative procedure which incorporates the appropriate stress-strain relation from the mechanical properties of the membrane material. This method has been employed with great success. (See, for example, Reference 6.)

By making use of Eqn. 1 and the values and dimensions in Table 2, the ORNL blast doors were designed to resist the expected overpressures. A yield strength of 33,000 psi was used for each membrane. While this is a "book value" and not an actually measured data item, it represents a lower bound on the actual yield strength. When it is used with Eqn. 1, it then gives a conservative (i.e., slightly exaggerated) estimate of the membrane deflection.

The ORNL blast door concept was based on a diameter near 36 inches, necessary to cover a 30-in. i.d. shelter entrance. The circular membranes were cut from 304L stainless steel sheet. Since the thickness of the membrane was a crucial factor in its response to the blast loading, stainless steel was chosen to prevent rust or corrosion from altering the chosen thickness. The edge beam supports were fabricated from mild carbon steel. A gas tungsten arc welding technique, using an

TABLE 2

Design Specifications of Yielding Membrane Blast Doors

Item	Doors at 50 and 100 psi Field Locations	Door at 200 psi Field Location
Membrane -		
Material	304L stainless steel	304 stainless steel
Yield Strength [a]	33,000 psi	33,000 psi
Thickness	0.050 in.	0.080 in.
Predicted deflection [b]	4.3 in. (50 psi); 8.6 in. (100 psi)	11.1 in.
Support Hoop (Edge Beam)-		
Material	Carbon steel	Carbon steel
Type	Hoop rolled from rectangular 1 X 2 1/2 in. bar stock [c]	Hoop rolled from 2-in. SCH 40 pipe [d]
Geometry	34 in. OD X 2 1/2 in. tall	35 in. OD; torus
Total Weight Of Assembled Door	85 lb	90 lb [e]

NOTES: (a) Book value; not actually measured.

(b) Deflections computed from Eqn. 1.

(c) Hoop actually fabricated from two pieces of 1/2 X 2 1/2-in. bar stock.

(d) Pipe hoop was filled with concrete after rolling; See Table 3.

(e) Includes approximately 30 lbs of concrete fill.

Inconel 82T filler wire, was used to join the two materials. A more detailed specification of the welding procedure can be found in Appendix A.

For the 200 psi overpressure, a rolled pipe hoop was used. The curvature of the pipe was expected to give good "angle of wrap" support to the welded membrane. In addition, the interior of the pipe was filled with concrete and vibrated so as to provide increased resistance to compression (See Table 3).

For the two lower overpressures, a rectangular bar was rolled into a hoop in order to form the edge support for the membrane. Two 1/2-in. thick hoops were rolled and welded to yield a 1-in. thickness. The flat edge of this hoop provided an excellent surface for the welding of the membrane. The cross-sectional area of this hoop was chosen to resist the compressive (hoop stress) load produced by the deforming membrane. A membrane tensile strength of 50,000 psi and a support hoop yield strength of 20,000 psi were used in these design calculations. The calculations indicated that a 1 X 2 1/4-in. rectangular cross-section would be sufficient; however, a 1/2 X 2 1/2-in. bar stock was available "off-the-shelf," and two such pieces were used in the interest of saving time and cost. The frame or support collar on which these blast doors rested was a lightweight design fabricated from rolled angle iron as shown in Fig. 8. Two sections of 2 X 2 X 1/4-in. steel angle iron were rolled into hoops to form the base of the support collar, while a hoop of 1 X 1 X 1/8-in. angle iron served as a rain lip. These hoops were joined by full circumferential seam welds. The collar weighted 65 lbs.

The support collar was designed to fit over an open-ended 2 ft. length of 30-in. diameter corrugated metal culvert, which simulated the vertical entryway to an underground blast shelter. A pair of hold-down anchors, fabricated from 4 ft. lengths of 4 X 4-in. angle iron, were attached to the support collar with 1/2-in. tie rods and were buried beside the metal culvert. These anchors were intended to keep the blast door and support collar from moving during the negative phase of the blast and were included for the purpose of this test only. In an actual

TABLE 3

Fill Mixture for Yielding Membrane Support Hoop (Pipe)

Constituent	Amount
Portland Cement	72 lb.
Sand	215 lb.
Water	36 lb.
Admixture (Grace WRDA 19, plasticizer)	8 oz.
Gravel (screened to 1/4 in. top size)	Added as Needed

Notes: (1) Not all of this total volume of mixture was required.

(2) The compressive strength of the cured aggregate was measured to be 8040 psi.

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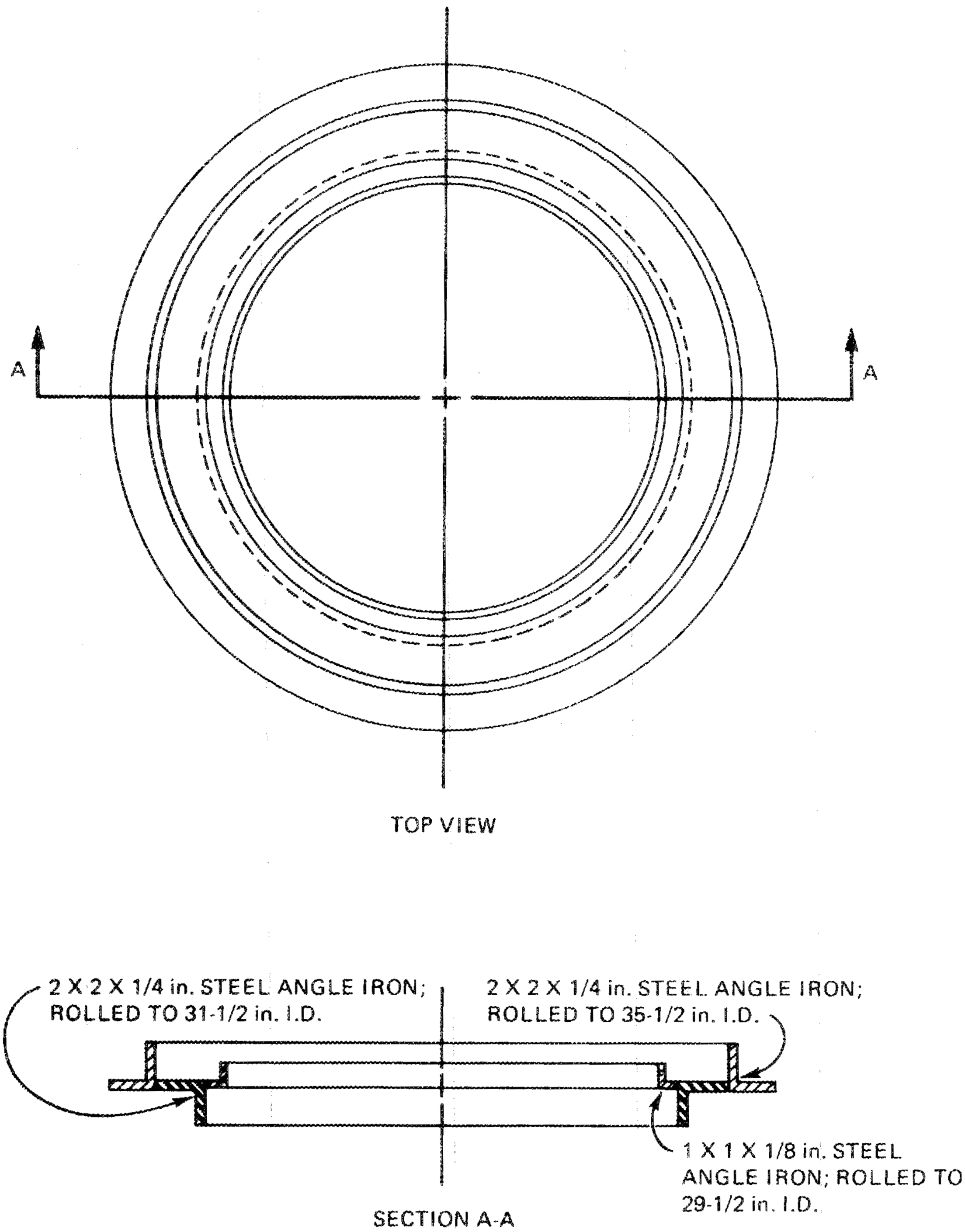

Fig. 8 Support Collar Design for Yielding Membrane Blast Doors

blast shelter construction, the support collar would be attached directly to the longer, well-anchored vertical entryway section.

Three identical support collars and hold-down systems were installed for the three blast doors. Photos of these installed support collars prior to the addition of the blast door appear as Figs. 9 and 10.

The elevated edge around the support collar (See Fig. 8 and 10) served as a guide for the building of an earthen windscreen. Earth was sloped from the top of this edge to grade level for the intended purpose of deflecting the debris and other dynamic effects of the blast.

Figure 11 is a photo of the blast door installed at the 200 psi field location. Note that eight hold-down tabs have been used to attach the blast door to its support collar. This construction was necessary solely for the purpose of this test to prevent damage to the door during the negative phase of the blast. In an actual shelter construction, some different hold-down mechanism, which allows the shelter occupants to open and close the door from the inside, would have to be installed. It should also be noted that these blast doors lack thermal protection, which is essential in guarding against the thermal pulse from nuclear weapons. Future tests of these doors will have to include some type of ablative covering.

The cost of fabricating each of the blast doors and the accompanying support collar appears in Table 4. Even with this limited prototype production level and a $40 per hour labor charge, these items were not that expensive. It would be expected that such items could be mass-produced at costs less than half of those in Table 4.

Once again, there was no active instrumentation in this set of experiments. Determination of the post-test condition, deformations, and/or failure modes was the primary objectives.

ORNL—PHOTO 0446—84

Fig. 9   Support Collar being Installed at the 50 psi Field Location

ORNL–PHOTO 0458–84

Fig. 10 Support Collar as Installed at the 50 psi Field Location

ORNL—PHOTO 0453–84

Fig. 11   Blast Door Installed on Support Collar at the 200 psi Field Location

TABLE 4

Shop Fabrication Costs for ORNL Yielding Membrane Blast Doors

Item	Material Cost	Labor Cost*	Total Cost
Yielding Membrane Blast Doors			
- with rectangular support hoop	$ 70	$440 (11 hr)	$510
- with pipe support hoop	140	360 (9 hr)	500
Support Collar	40	300 (7.5 hr)	340

*Number of hours used in fabrication is shown in parentheses; costs were computed from charges of $40/hr.

3. RESULTS

The explosion of the DIRECT COURSE charge occurred about noon on October 26, 1983. Figures 12 and 13 show a portion of the detonation sequence. In Fig. 13 the blast wave (shock wave) can be seen propagating as a hemisphere centered at the point of explosion. The edge of the blast wave is visible due to the difference in the density of the air in front of and behind the wave. It is this blast wave which creates the sudden pressure increases and causes damage to structures.

The DIRECT COURSE blast was more energetic than anticipated. Measured overpressures at all field locations were 10 to 20% greater than predicted.

3.1 TEST RESULTS FOR THE SCALE MODEL BLAST SHELTERS

The three 1/4-scale shelters were tested at field locations with expected overpressures of 50, 100, and 200 psi. All three shelters survived the blast. Figure 14 illustrates the typical post-test condition of the shelters.

Other than a slight, concave deformation of the shelter body at the entry joint of the 200 psi shelter as shown in Fig. 15, no damage or distortion to the entryway or to its connections was observed at any of the three overpressures. As can be seen in Figs. 16 and 17, there was no damage to the low-cost end enclosure at 50 psi; however, at the 200 psi field location, the angle iron support had buckled as shown in Fig. 18. This end enclosure had moved approximately one-quarter shelter diameter (i.e., 6 inches) into the shelter, partially blocking the entryway. There was no other damage to the 200 psi shelter; most of the occupants of such a full scale shelter would not have been injured by this degree of structural damage.

Figure 19 shows that the conical end of the shelter survived as expected due to its excessive thickness. The actual thickness (0.109 inch) of this end of the 1/4-scale shelter would represent 1/2 inch plate in full size.

ORNL—PHOTO 3136—84

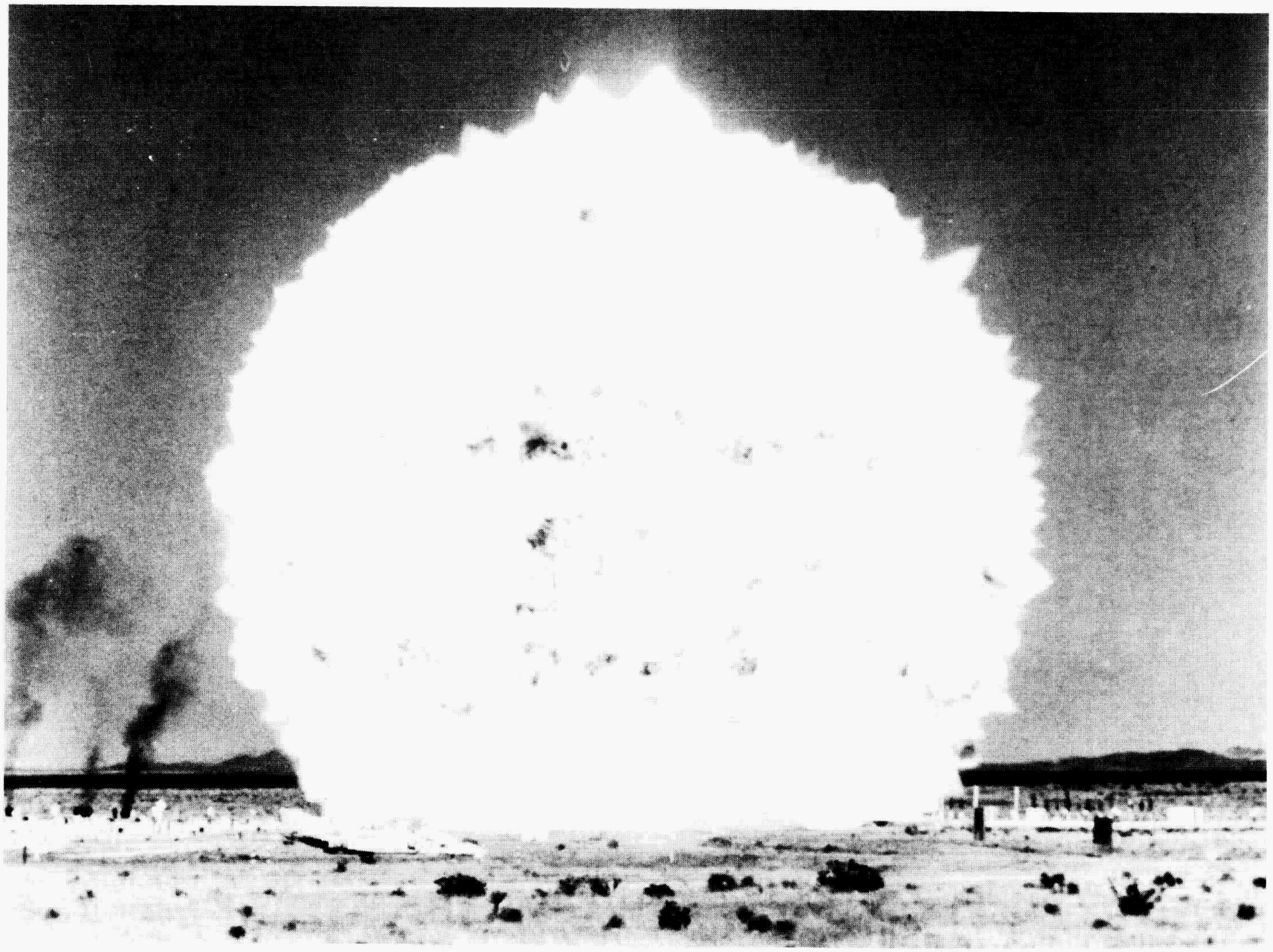

Fig. 12 Detonation of DIRECT COURSE Charge

ORNL—PHOTO 3137–84

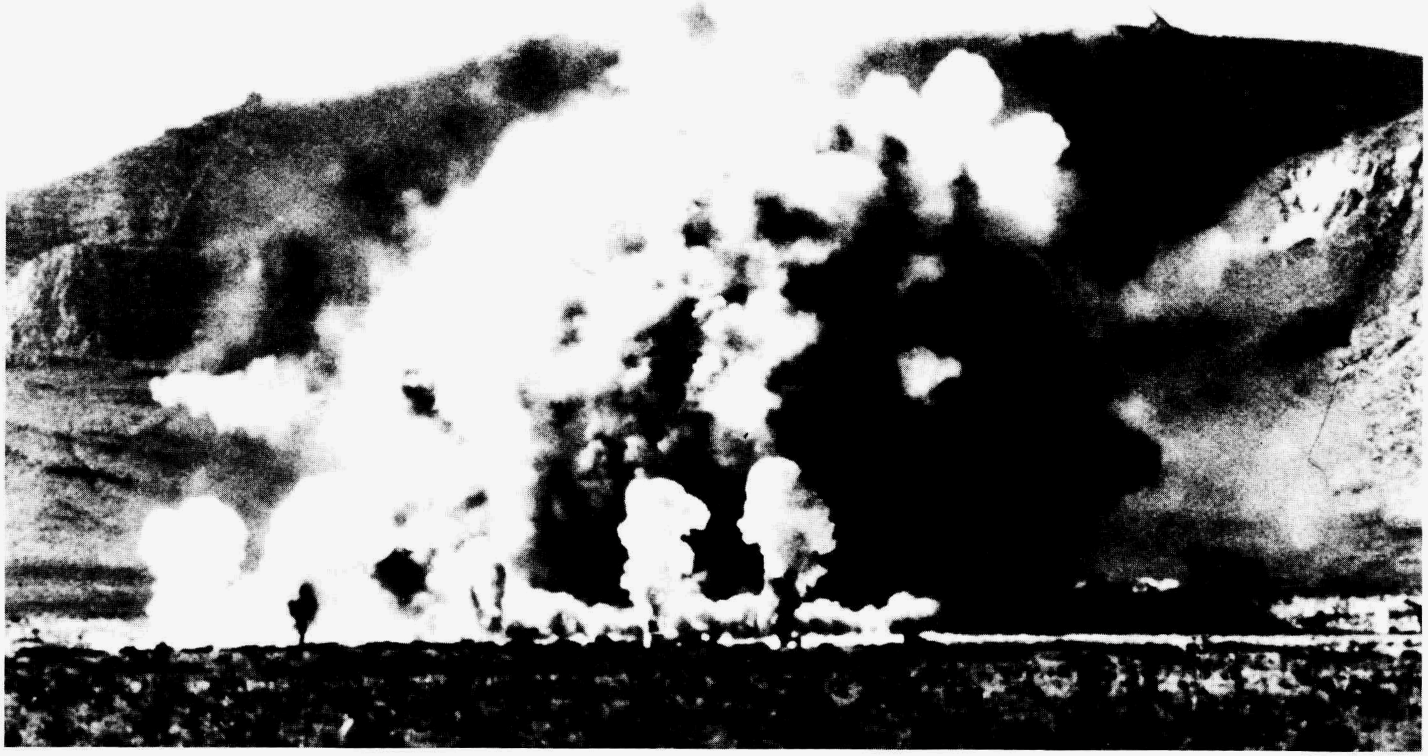

Fig. 13   Blast Wave Propagating from DIRECT COURSE Explosion

ORNL—PHOTO 0444–84

Fig. 14 Post-Test Condition of the Scale Model Blast Shelter at the 200 psi Field Location

ORNL—PHOTO 0441—84

Fig. 15 Post-Test Condition of the Entryway for the 200 psi Shelter

ORNL—PHOTO 0430–84

Fig. 16   Post-Test Condition of the Entryway for the 50 psi Shelter

ORNL—PHOTO 0435—84

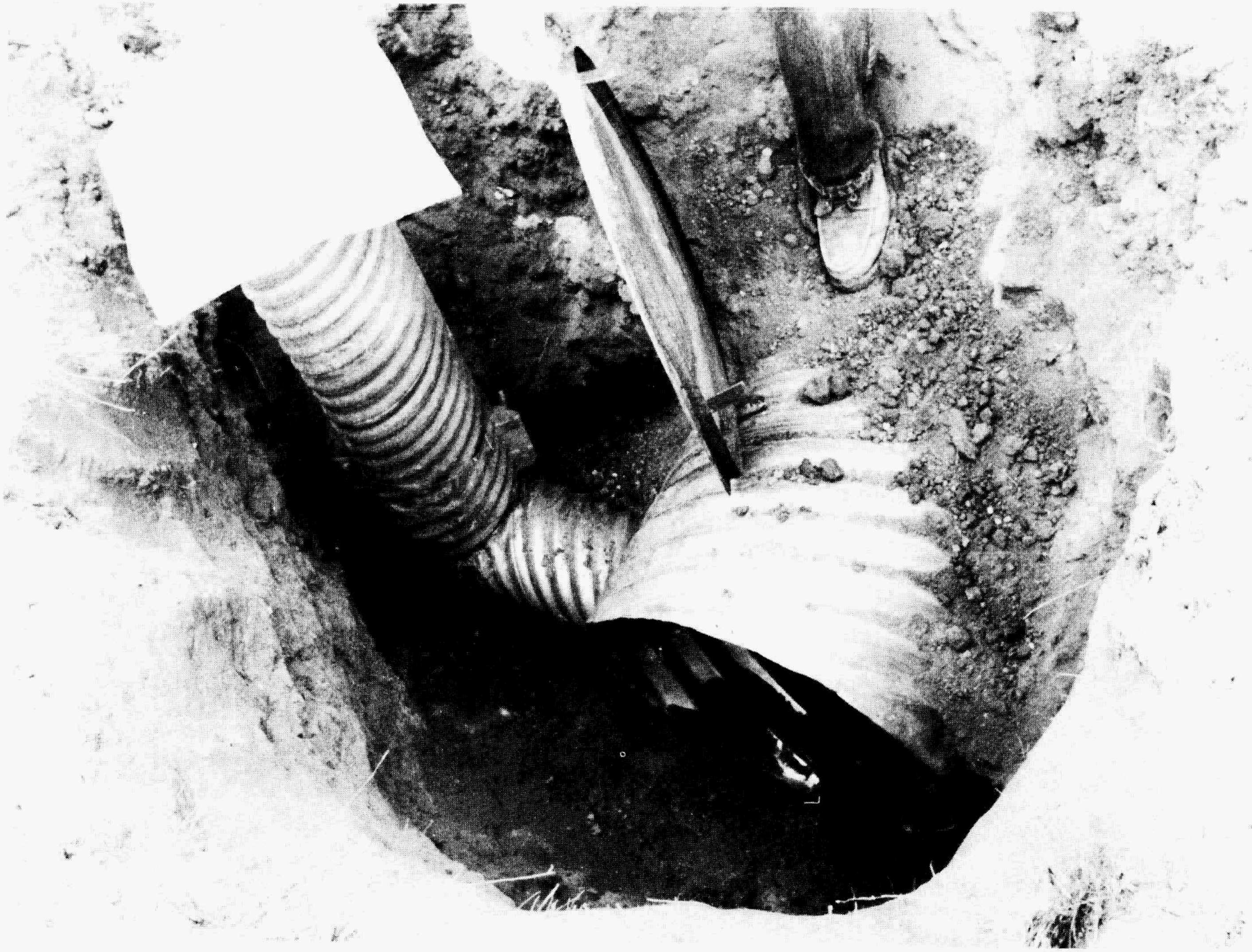

Fig. 17   Post-Test Condition of the Low-Cost End Closure for the 50 psi Shelter

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Fig. 18 Post-Test Condition of the Low-Cost End Closure for the 200 psi Shelter

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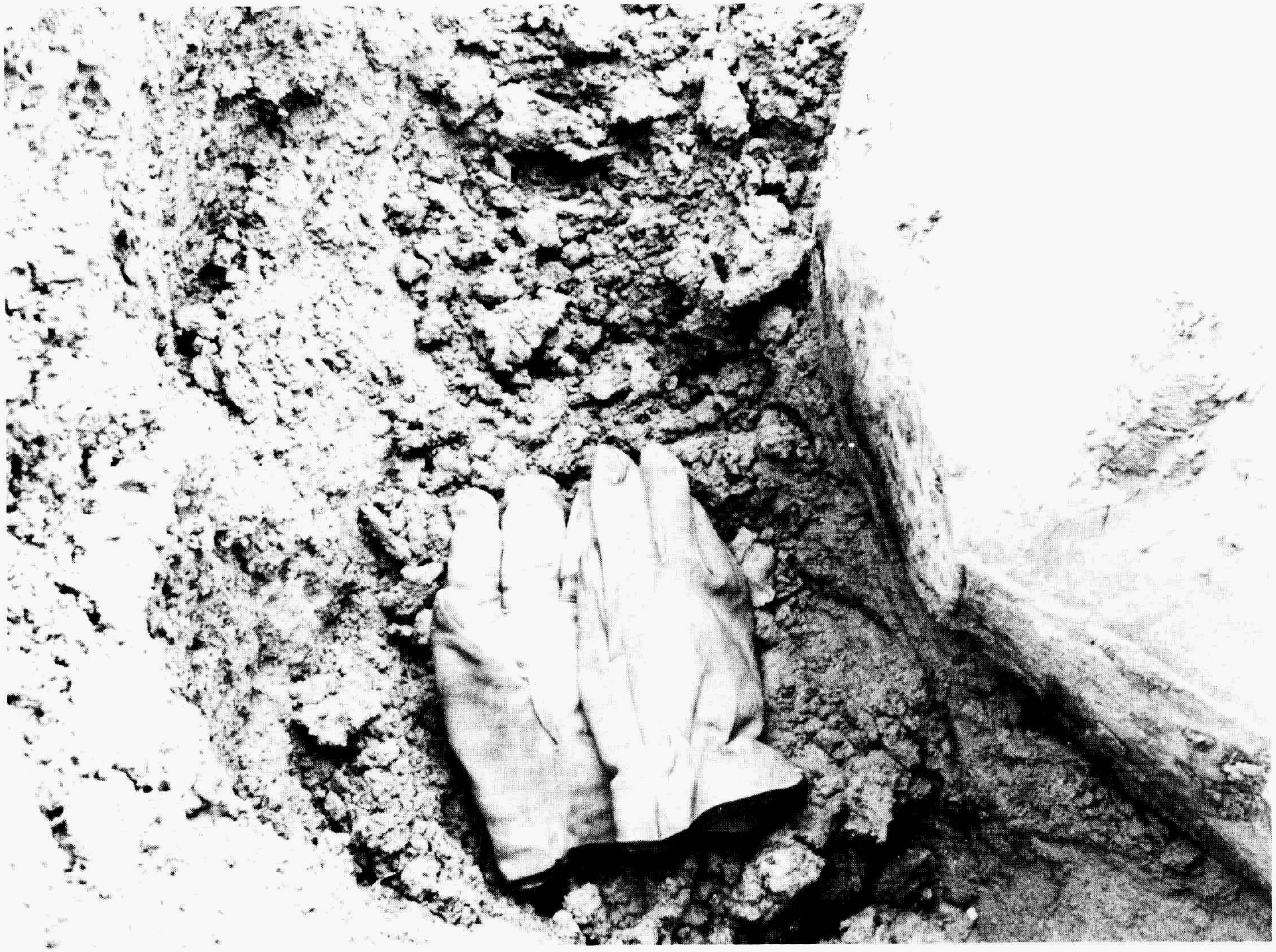

Fig. 19   Post-Test Condition of the Conical End Closure for the 200 psi Shelter

3.2 TEST RESULTS FOR THE YIELDING MEMBRANE BLAST DOORS

The three full-size blast doors were also tested at field locations with expected overpressures of 50, 100, and 200 psi. Each of these doors and their support collars successfully resisted the actual blast loading. The post-test condition of the three blast doors and support collars is shown in Figures 20 through 25.

Table 5 indicates the observed blast effects on the yielding membrane doors and their support collars. An initial examination of the observed membrane deflections revealed that they were about half of what had been expected from the theory (Eqn. 1). In seeking an explanation for the discrepancy between the theory and the observed membrane deflections, there are two possible lines of reasoning: (1) the theory is in error or its assumptions do not apply to this set of tests and (2) the mechanical properties of the material (yield strength) were much stronger than expected.

The yielding membrane theory has been repeatedly proven in blast gauges; however, these structures are typically thin foils of a few mils thickness and are only a few inches in diameter. One of the assumptions in the theory states that the blast pressure has an infinite duration. This assumption is exceedingly adequate for small membranes with deformation times in the order of microseconds; the blast overpressure effectively remains the same during this period. However, the larger membranes on these blast doors should take several milliseconds to deform. During this period the overpressure, particularly at the higher pressure levels, decreases significantly. Possibly then, these blast doors responded not to a constant, maximum overpressure but to some lesser, time-averaged value.

Furthermore, the mechanical properties of the yielding membrane materials were not accurately known. Using Eqn. 1 and the values of the observed overpressure and deformations, one can compute the yield strength required for such observed behavior. Performing this computation for each door results in yield strengths which are higher than one

ORNL—PHOTO 0432—84

Fig. 20 Post-Test Condition of the Blast Door and Support Collar at the 50 psi location

ORNL–PHOTO 0292–84

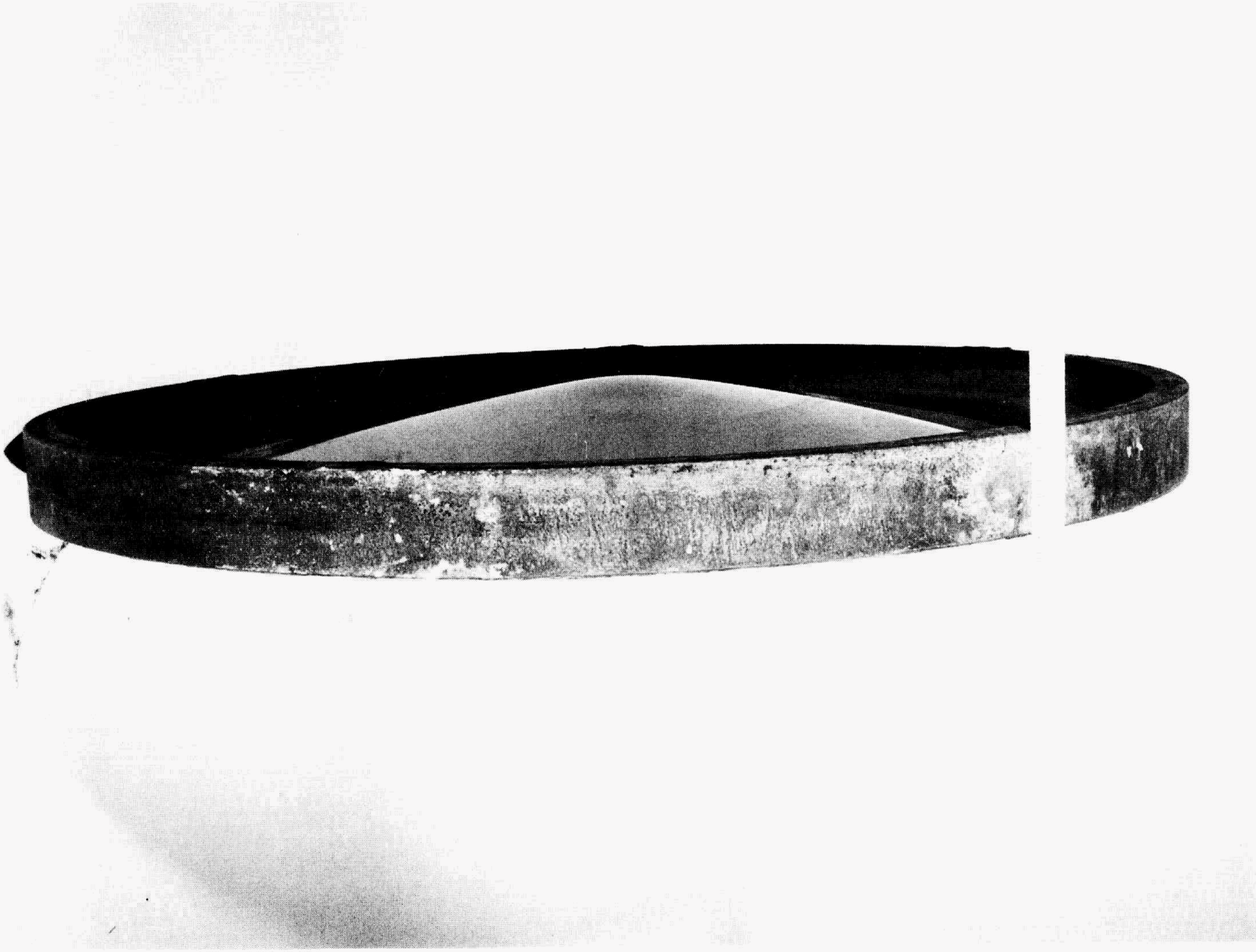

Fig. 21 Edge View of the Blast Door Tested at the 50 psi Location

ORNL—PHOTO 0438—84

Fig. 22 Post-Test Condition of the Blast Door and Support Collar at the 100 psi Location

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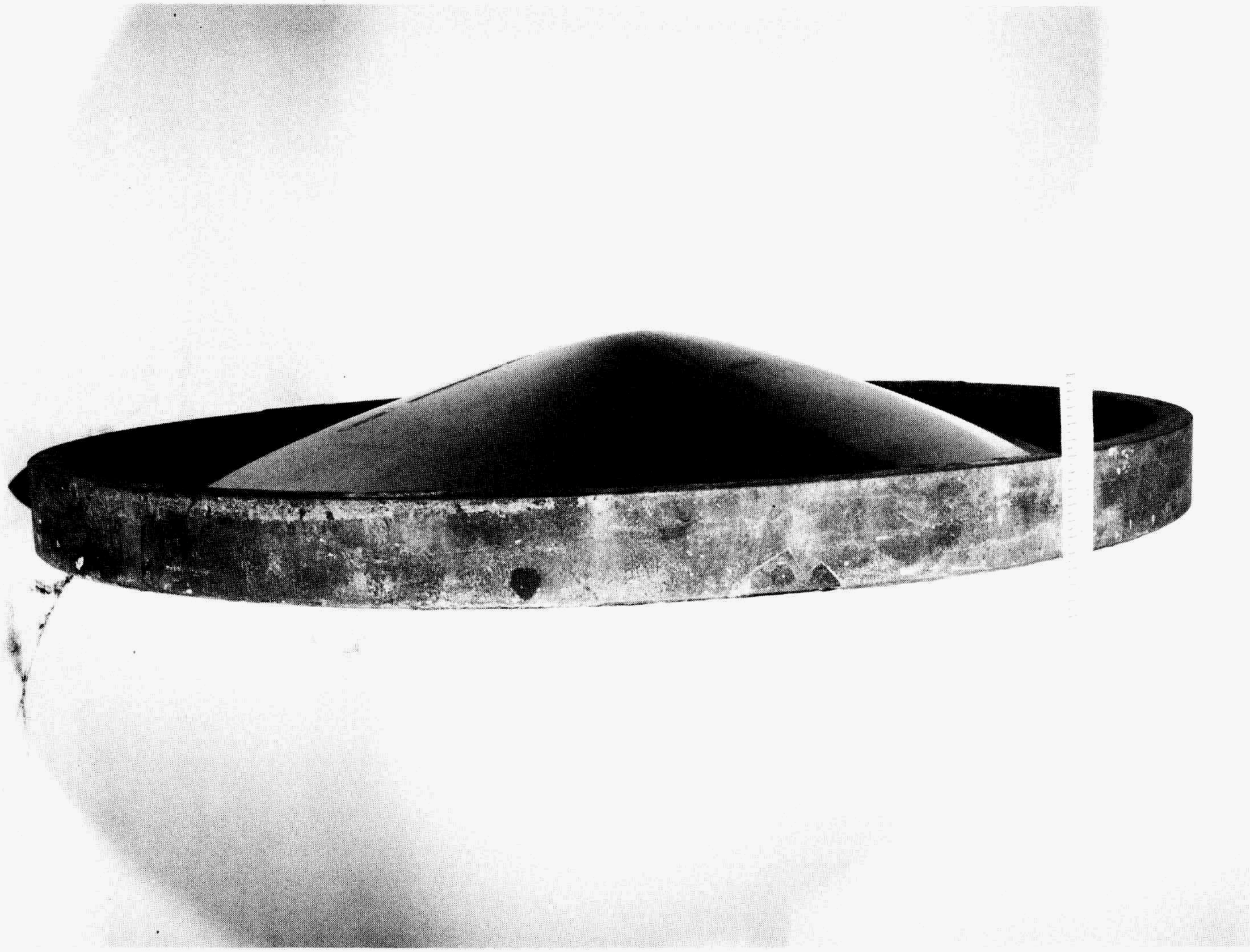

Fig. 23   Edge View of the Blast Door Tested at the 100 psi Location

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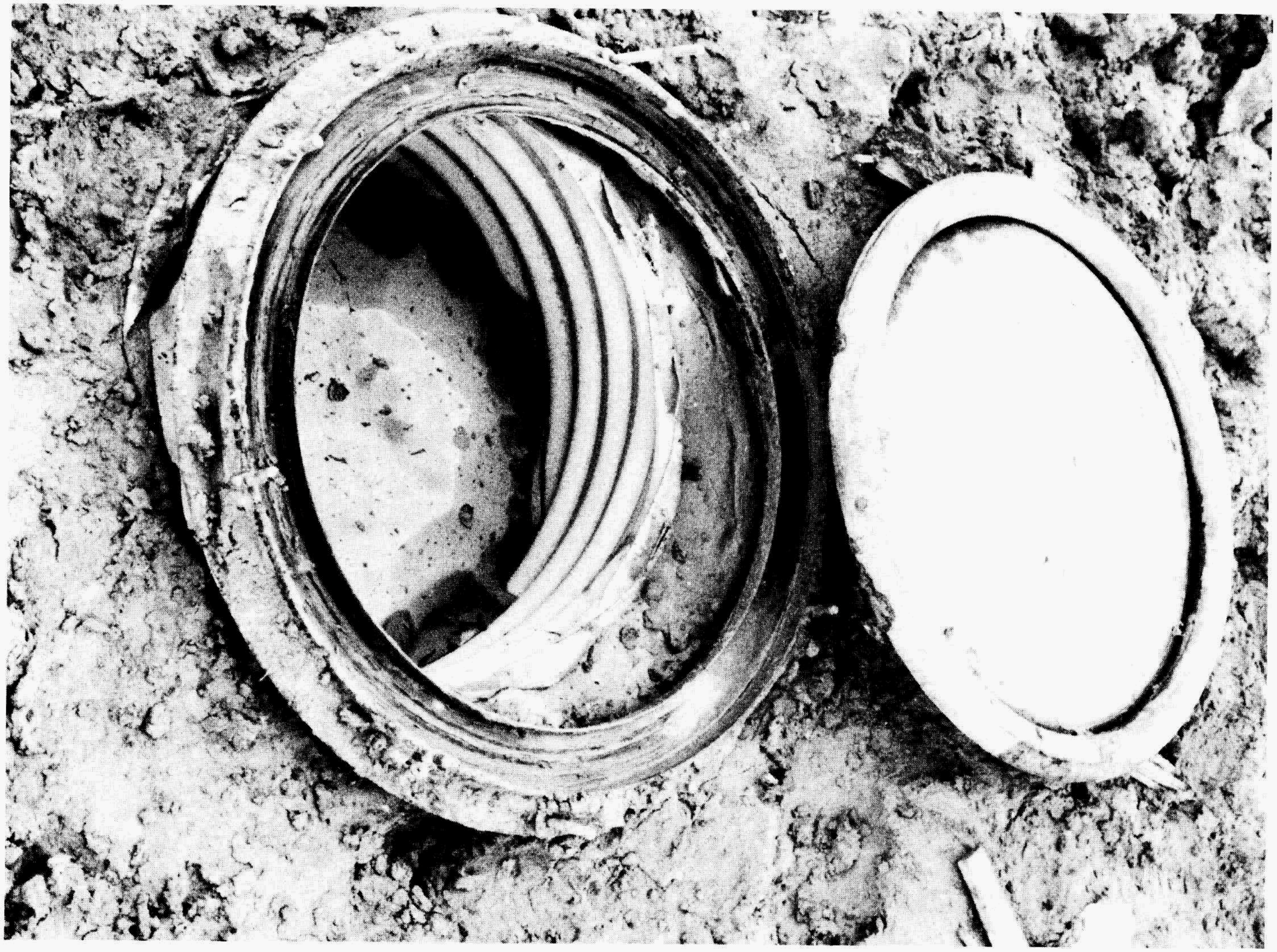

Fig. 24   Post-Test Condition of the Blast Door and Support Collar at the 200 psi Location

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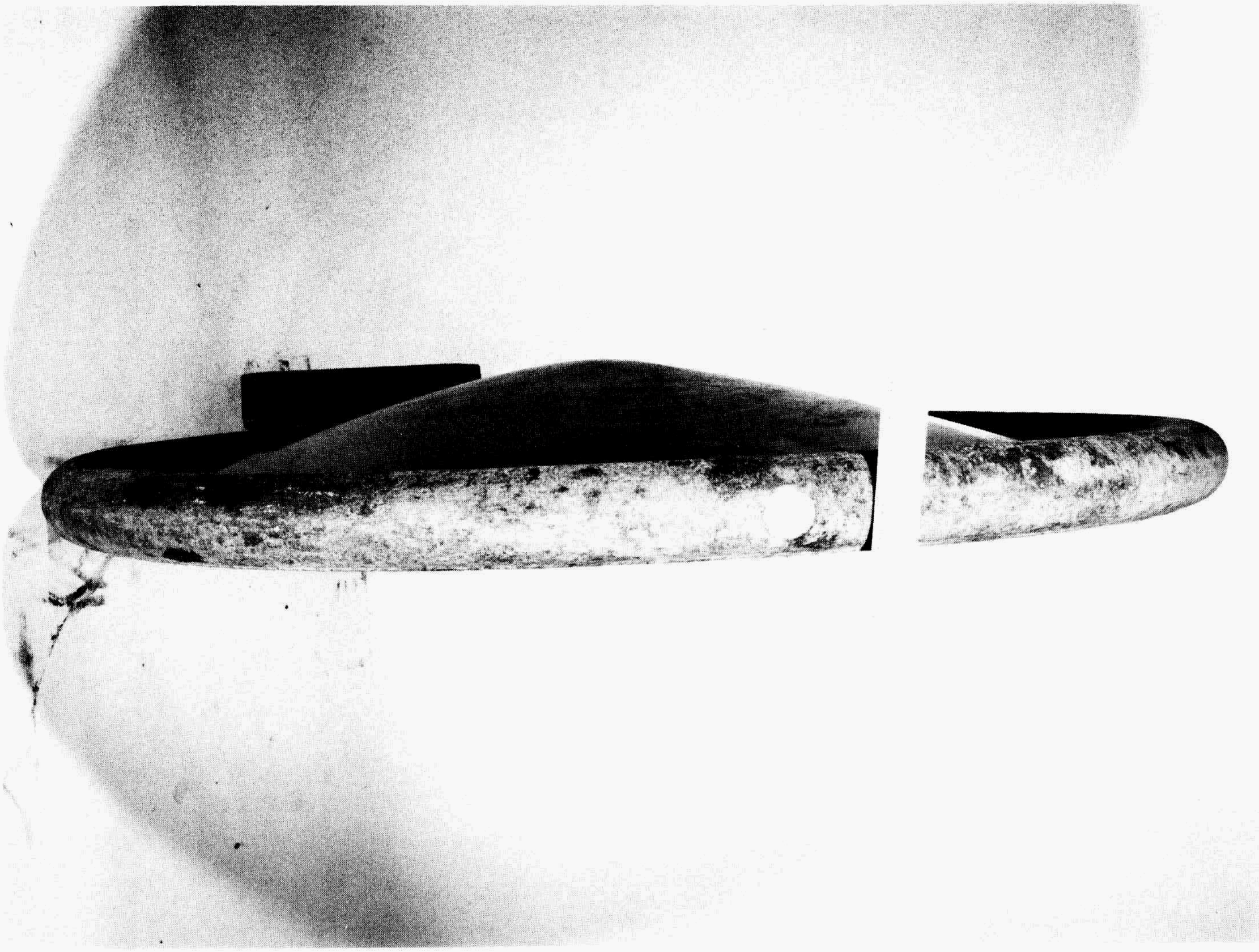

Fig. 25 Edge View of the Blast Door Tested at the 200 psi Location

TABLE 5

Results of Blast Tests on Membrane Doors

Predicted overpressure (psi)	50	100	200
Reported overpressure (psi)	65[a]	118[b]	225[c]
Membrane thickness (in.)	.050	.050	.080
Edge support hoop[d]	1 X 2.5" tall Mild Steel	1 X 2.5" tall Mild Steel	2"sch 40 steel pipe, Grouted
Door OD (in.)	34	34	35
Maximum depression of membrane (in.)	2.5	5.2	4.25
Downwind eccentricity of dimple (in.)	3.0	3.5	3.5
Depression of support collar into soil[d] (in.)	3.75	3.875	4.0

NOTES:
(a) Source: Reference 8 (BRL/WES)
(b) Source: Reference 8 (WES)
(c) Source: Reference 8 (Interpolated from BRL data)
(d) There was no observable post-test distortion of edge support or of support collars.

would expect for stainless steel sheet; a range of 65,000 to 95,000 psi is obtained. It is doubtful that the unknown strength of these materials is the sole explanation for the discrepancy between theory and observation.

A simple, mathematical model using the equations of motion was used in order to study the effect of the rapidly decreasing overpressure. From the familiar equations of dynamics,

$$v = \int a \, dt, \qquad \text{(Eqn. 3)}$$

and

$$H = \int v \, dt, \qquad \text{(Eqn. 4)}$$

where a is the acceleration of the membrane,

v is the velocity of the membrane,

and

H is the membrane's displacement.

Once the time dependence of the acceleration is known, the above equations can be employed (using numerical integration, for example) to find the membrane deflection as a function of time.

The acceleration can be related to the force on the membrane:

$$F = ma \qquad \text{(Eqn. 5)}$$

where m is the mass of the membrane,

and F is the net force applied to the membrane,

The acceleration can therefore be expressed as

$$a = \frac{F}{m} . \qquad \text{(Eqn. 6)}$$

The forces on the membrane result from the sudden application of the overpressure (in the direction of motion) and the resisting tensile force in the membrane itself. At any instant in the deflection of the membrane, such as the one shown in Fig. 26, these forces can be combined into a net force:

$$F = \frac{\pi}{4} P \, D^2 - \pi D \;\; s \;\; T \;\; (\sin\alpha), \qquad \text{(Eqn. 7)}$$

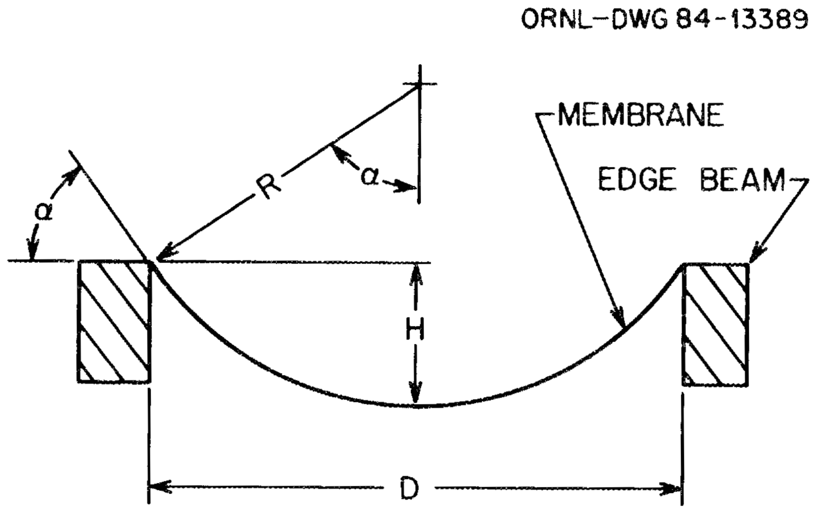

Fig. 26 Mathematical Model of Membrane Deflection

where those variables not defined immediately above may be determined from Fig. 26 and Section 2.2. The first term above comes from the decaying overpressure; the second represents the resisting tensile force in the yielding membrane. The net force obviously varies with time, since both the overpressure and the angle α change as the membrane deflects.

The decay in the incident overpressure can be found in Reference 5. That is,

$$P = f\ (P_{incident}, t). \qquad \text{(Eqn. 9)}$$

For any change in the membrane deflection, the angle α may be found from the geometry of Fig. 26:

$$R^2 = (R - H)^2 + (D/2)^2, \qquad \text{(Eqn. 10)}$$

or

$$R^2 = R^2 - 2RH + H^2 + (D/2)^2, \qquad \text{(Eqn. 11)}$$

from which

$$R = \frac{4H^2+D^2}{8H} \quad . \qquad \text{(Eqn. 12)}$$

Also,

$$\sin\alpha = \frac{D/2}{R} = \frac{(D/2)\ (8H)}{4\ H^2 + D^2}, \qquad \text{(Eqn. 13)}$$

or,

$$\sin\alpha = \frac{4\ H\ D}{4\ H^2 + D^2}. \qquad \text{(Eqn. 14)}$$

Having the pressure-time relation as in Eqn. 9 and the physical determination of the angle in Eqn. 14, one can compute the net force causing the motion of the membrane from Eqn. 7. This variation in the

force provides the means by which the time dependence of the acceleration can be determined; hence, the membrane motion can be investigated.

The use of the force as given in Eqn. 7 and the application of Eqn. 6 to this problem involves the assumption that the membrane moves as single mass; that is, no effect of the curvature of the membrane on the distribution of its moving mass has been included in this analysis. While this is most certainly a simplifying assumption, it should give a good first-order approximation to this complicated dynamic behavior.

This method was applied to each of the three doors through the use of a computer program. Fig. 27a shows the overpressure decay, as obtained from Reference 5, for both the expected incident overpressure and the measured incident overpressure. The area bounded by these two curves for each field location represents an idealization of the pressure decay as observed at the DIRECT COURSE event.

Figure 27b contains the results of the analysis using the above method, and Table 6 summarizes these results. Membrane yield stress values of 50,000 psi were used in the analysis. It should be noted that the deformation of each of these membranes was theoretically completed within about 3 ms from the arrival of the blast wave.

Table 6 shows that the previous theory (Eqn. 1) overpredicted the membrane deflections, particularly at the higher pressure level where the overpressure is decreasing rapidly. The computer model, which includes this decaying overpressure, can more closely explain the behavior of the membranes; however, this is not an indication of failure for the theory but is instead an indication of the limitations of the theory in handling overpressure variations during the membrane deflection. For weapons in the megaton range, the longer duration of the overpressure would result in a very nearly constant value of pressure during the short deflection time for these membranes. In that case, the theory (Eqn. 1) would be fully adequate for design purposes.

Also of concern in the results of the blast test was the depression of the door and frame into the ground (See Table 5). While there was no

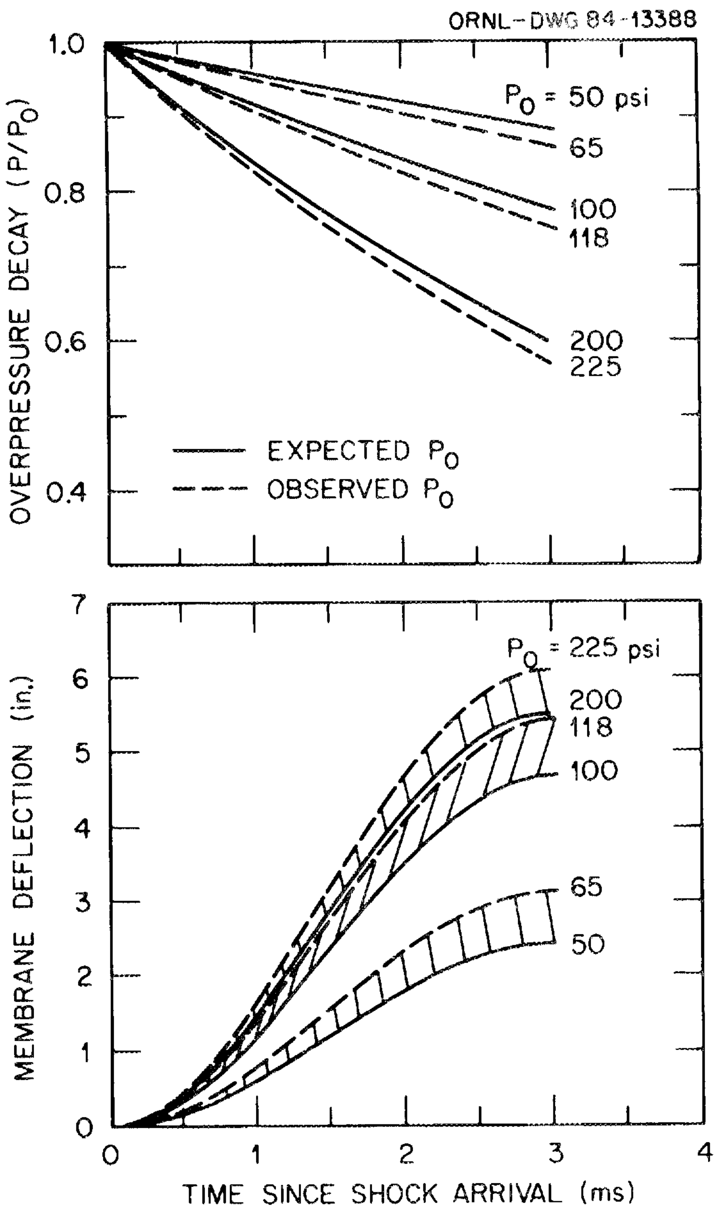

Fig. 27(a) Decay of Overpressure at DIRECT COURSE Event

Figs. 27(b) Membrane Deflection as Predicted by Computer Model

TABLE 6

Comparison of Membrane Deflection Theory to Computer Model and to Observed Deflections

Expected Overpressure (psi)	50	100	200
Reported Peak Overpressure[a]	65	118	225
Membrane Deflection[b] (in.)			
From Previous Theory [c]	2.8-3.7	5.6-6.7	7.3-8.3
From Computer Model[d]	2.4-3.1	4.7-5.5	5.5-6.1
Observed[a]	2.5	5.2	4.25
Time for Total Membrane Deformation (Milliseconds) (From Computer Model)	3.02	3.04	2.98

Footnotes:

a See Table 5

b Range of data indicates deflections from expected overpressure and from observed overpressure, respectively

c See Eqn. 1

d See Eqns. 3 through 14 and Fig. 27

observed deformation of the support collar, a wider "shoulder" is obviously needed to provide greater resistance to being pushed into the soil. The corrugated metal culvert, which simulated a shelter entryway, was damaged at the 200 psi location (Fig. 24). No such damage was observed at either of the other two field locations. It is not known for certain whether the observed damage was caused by the actual blast effects.

Apparently, the downwind displacement of the support collar at the 200 psi location (Fig. 24) was not caused by the initial air shock. The tie-rods connecting the support collar to the deadman anchors were extended, indicating that the blast door had been partially lifted by the negative phase of the blast. The horizontal movement apparently occurred after this time, since any motion during this period would have been in an upwind direction with the accompanying negative phase blast winds. A large amount of water from an experiment located upwind from this door was propelled in the direction of the door and support collar by the blast. The time lag necessary for transporting this amount of water is commensurate with the apparent time of the support collar's downwind displacement.

No other failure or deformation to the support hoops for the membranes or to their welds was observed. The structural integrity of these structures was greater than anticipated, especially at the 200 psi location.

4. CONCLUSIONS AND RECOMMENDATIONS

The entryway design for the corrugated metal blast shelter proved successful and showed great promise for improving both the cost and hardness of such shelters. The clamped joint of the vertical section of the entryway did not fail or distort, indicating that field welding of such structures is possibly unnecessary. The welded joints of the TEE section held together superbly; however, based on the observed distortion at the shelter body, the apparent failure mode will be for the shelter body to yield at the TEE section joint. This is to be expected, since the entryway disturbs the soil arching phenomenon which gives strength to the cylindrical shelter body.

The blast shelter's low-cost end closure, which was fabricated from rolled angle iron and sheet metal, survived the 65 psi blast but failed by buckling under the 225 psi overpressure. While it is not certain, this failure might have been caused by inadequately compacted backfill and the absence of sufficient soil arching to provide the necessary strength. This design concept, which appears to be promising, should be further developed. In particular, the support ring, when scaled to full size would be made from a 4 X 4 X 1/2 inch angle iron rolled to 9 feet diameter. This is a rather large structure which might have many disadvantages (transport, erection, etc.) over the bolted end structure of the Donn Metal Products design.

The yielding membrane blast door concept proved to be remarkably successful. Not only did the three doors survive the blast with smaller deflections than expected, but they also resisted higher overpressure than was anticipated in their design.

The novel, rolled angle iron design for the frame (support collar) for each blast door also proved to be successful. It is possible that shop fabrication, transport and field installation of this structure could be accomplished in less time and at less cost than erecting a form and pouring a concrete footing to serve as such a door frame.

The observed problem with the depression of the door and its support collar into the ground upon blast loading could be reduced by creating a wider shoulder for the support collar and/or by providing some circumferential support for the surrounding soil. Alternatively, this collar design could be elevated on a low berm of earth so that even if it is depressed, it will not allow water to pool and drip into the shelter.

It is recommended that the next step in the design of this blast shelter and blast door should accurately reflect a working model. A full-size shelter should be built, tested for habitability, and subjected to blast loading. Both clamped and welded joints should be tested. Design modifications to the blast door and its support collar should include the necessary thermal protection, hinges, latches, and other operating features as required in actual service in a blast shelter.

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Appendix A

Welding Procedure Specifications

Adapted from Oak Ridge National Laboratory's "Welding Procedure Specification, No. WPS-2102;" Revision 0, December 1969."

GAS TUNGSTEN-ARC WELDING OF CARBON STEEL TO CHROMIUM-NICKEL STAINLESS STEEL

PROCEDURE QUALIFICATION

Specification: ASME Code Section IX.

BASE METAL		BASE METAL
Alloy or Grade:	Steels having tensile strength between 45,000 and 72,000 psi.	304L CR-Ni Sheet
Specification:	Section II	Same
P-Number Group:	P-1	P-8
Form/Thickness:	Any 0.035-0.5-in.	Same

FILLER METAL

Classification:	ERNiCr-3 (Inconel 82T).
Specification:	SB-304
F & A-Numbers:	F-43
Form of Filler:	Straight bare welding rod.
Identification:	Complete, original label on container. Classification mark on each rod.
Filler Surface:	Bright smooth surface, free of pits grooves, oxide, and foreign material.
Filler Storage:	In sealed original unit container.

SHIELDING GAS

Arc Shielding: 99.995% (minimum) argon.

JOINT BACKING

Backing Gas: 99.995% (minimum) argon.

Backing Strip/ Ring — None required.

WELD GROOVE PREPARATION

Joint Geometry: Lap joint.

Cutting Process: Oxyacetylene (C-Steel only), or plasma-arc.

Cutting Defects: Machine or grind to remove burrs, laps, gouges, etc. to produce smooth joint surfaces. Remove 0.050 in. metal from plasma-arc cut surfaces on Cr-Ni Steel.

Scale and Oxide: Remove within 0.5 in. of joint (C-Steel), or 1 in. (Cr-Ni Steel).

Foreign Material: Remove within 2 in. of joint (C-Steel), or 4 in. (Cr-Ni Steel).

WELD JOINT SET UP

Assembly and Fixtures: Provide the necessary clean fixtures to align and support parts during welding. Use temporary welds only where necessary.

Provide flow channels and baffles that will prevent contamination of the backing gas.

Protect weld area to exclude foreign material and drafts that might contaminate inert gas shielding.

Cleaning Check: Immediately before welding, inspect groove surfaces and base metal for foreign material by wiping with clean white cloth.

Tack Welding: Deposit short thin beads equally spaced along root; remove oxide and defects.

WELDING PROCESS, CURRENT AND EQUIPMENT

Process: Gas Tungsten-arc, argon shielded.

Process Control: Manual.

Current: Direct current, electrode negative (straight polarity).

Current Source: Rectifier or generator having drooping volt-amp characteristic, with foot control for continuous control and slope of current over a 10-to-1 range.

Arc Starter: High-frequency oscillator if available.

Welding Torch: Suitable manual gas tungsten-arch torch.

Electrode: Thoriated tungsten Classification EWTH-2, ASTM-B297.

Flow Meters: Suitable argon flow meters.

Gas Lines: Metal or plastic tubing. Substitute backing gas lines may be latex rubber tubing in new condition.

PREHEAT AND INTERPASS TEMPERATURE

Preheat Temperature: 60-100°F.

Preheat Equipment: Gas torch, resistance heater or similar equipment.

Temperature Check: Contact pyrometer or similar equipment.

WELDING OF JOINT

Joint Welding One (1) layer, one (1) bead; use 40 amp (negative DC current) with 0.045 inch diameter rod. Torch: 1/16 inch diameter tungsten, 0.5 inch nozzle diameter, 15 cubic feet per hour argon gas flow. Backing gas: 15 cubic feet per hour required.

Torch Lead Angle: 0-15°

Electrode Tip: Conical with 40°-60° included angle; minimum radius instead of point.

Electrode Extension: 1/4 to 3/8 inch.

Travel Direction: Forehand; upward when weld axis is not level.

Bead Type: Stringer.

Technique: Position torch. Start gas preflow and purge air from gas lines, torch, and arc-strike area.

Start arc at low current; when arc is stable, upslope current to welding level. Strike arc by means of high-frequency spark or light touch of electrode.

Move torch at a uniform rate. Oscillate torch only if necessary. Regrind electrode to maintain required tip shape and to remove metal pickup and oxide.

Hold rod at a low angle with end in the shielding gas. Feed rod at a uniform rapid rate into the leading edge of the weld pool. Add rod during all welding. Remove oxidized ends of used rods.

Before breaking arc, fill crater and reduce weld pool to smallest possible size by downsloping current.

Maintain gas postflow that will produce bright surfaces on weld and electrode.

CLEANING OF WELD BEADS - Remove oxide and other deposits (particles and from each weld bead and adjacent base metal.

PEENING Do not peen.

DEFECTS

Examine each weld bead and each crater for cracks, holes, incomplete fusion, partial joint penetration, overlap, undercut, underfill, tungsten inclusions, heavy oxide, and other defects.

Check size and reinforcement of weld. Check that each bead has normal smooth surface and contour, and merges smoothly with adjacent beads or base metal.

Remove weld defects by grinding or filing.

Before depositing each bead, examine weld groove and adjacent base metal for cracks, laminations, holes, and other defects.

POSTWELD HEAT TREATMENT

Do not heat treat.

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In October 1983 the Defense Nuclear Agency (DNA) sponsored a high-explosive blast test, nicknamed DIRECT COURSE. This event simulated the blast effects from a one-kiloton nuclear detonation and provided an environment for the testing of selected blast and fallout shelters for their structural integrity.

Under work for the Federal Emergency Management Agency (FEMA), the Oak Ridge National Laboratory (ORNL) fielded a set of experiments at the DIRECT COURSE

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10. ABSTRACT (Cont'd)

event which were directed toward reducing the cost of blast shelter for small groups of people, such as workers incritical industries (keyworkers). Six items were tested: three scale models of a corrugated metal blast shelter and three full-size blast door closures for such a shelter.

The three shelter survived blast overpressures up to 2.55 MPa (225 psi), a level which is equivalent to being approximately 800 m (0.5 mile) from a 1 megaton nuclear detonation. Each shelter model was 180 cm (6 ft.) long by 60 cm (2 ft.) indiameter, was buried about 60 cm (2 ft.) below ground level, and represented a 1/4-scale version of a full-size blast shelter which would be capable of supporting 12 to 18 occupants.

The three full-size, 90 cm (35 in.) diameter, blast doors for such a shelter also successfully resisted the same range of blast overpressure. Each door weighed less than 45 kg (100 lb) and incorporated a novel, yielding-membrane design. These sheet metal membranes were between 1.3 and 2.0 mm (0.050 and 0.080 in.) thick and were supported by an edge beam (hoop).

It is anticipated that such structures, both shelters and blast doors, can be incorporated into a blast shelter concept which can be constructed for less than $500 per shelter occupant.

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